Economic Dynamics of Orbital Debris: Theory and Application

Nodir Adilov[1], Peter J. Alexander[2], and Brendan M. Cunningham[3]

[1] Department of Economics and Finance, Purdue University Fort Wayne, 2101 E. Coliseum Blvd., Fort Wayne, IN 46814, United States, adilovn@pfw.edu
[2] Federal Communications Commission, 445 12th Street SW, Washington, DC 20554, United States, peter.alexander@fcc.gov
[3] Department of Economics, Eastern Connecticut State University, 83 Windham Street, Willimantic, Connecticut 06226, United States, cunninghambr@easternct.edu

ABSTRACT

The study presents findings from theoretical economic models of business activity in orbital space. The effects of orbital debris levels on the economic costs of satellite operators and how economic forces contribute to the accumulation and mitigation of orbital debris are addressed. Using a dynamic economic model framework, the study forecasts future levels of debris and economic activity in orbital space under different policy choices.

1 INTRODUCTION

1.1 Introduction to the Economics of Orbital Debris

Orbital space is a global common; that is, orbital space is non-excludable, but rival. This implies that any nation – typically, an organization within a nation – with the requisite technological capability can utilize orbital space, but cannot occupy orbital slots or use the associated spectrum already utilized by another nation or organization.

Orbital debris, an externality generated by expended launch vehicles and damaged or nonoperative satellites, reduces the expected economic value of orbital activities by interacting with operational satellites or other space vehicles, damaging and sometimes destroying them. Orbital debris is also self-propagating: collisions between pieces of debris create a greater numeric quantity of additional (smaller) pieces of debris. Using economic terminology, the use of orbital space generates a negative externality because the orbital debris generated by one economic actor imposes costs on other economic actors.

1.2 Brief Background

The National Aeronautics and Space Administration (NASA) defines debris as non-functional human-made space objects [1]. Initially, debris is created from the upper stages of expended launch vehicles when a satellite is launched. Additional debris is created by the satellites themselves, both as they reach the end of their productive lives and break up, and as the result of impact with debris or with other satellites, among other things. Debris can damage or destroy communication, weather, navigational, governmental, and military satellites.

According to NASA [2], 42 percent of total extant debris is fragmentation debris (resulting primarily from the break-up of satellites), 22 percent is non-functional spacecraft, 19 percent is mission related debris, and 17 percent is rocket bodies. There are approximately 21,000 human-generated radar-tracked pieces of debris measuring over 10 centimeters (cm), 500,000 untracked pieces of debris between 1 and 10 cm, and over 100,000,000 untracked pieces of debris between .1 and 1 cm in Earth orbit [1].

The product of mass and relative velocity of debris determines its destructive force. All else equal, a collision with a piece of debris greater than 10 cm will likely destroy a satellite and generate significant amounts of additional debris. Debris greater in size than 1 centimeter but less than 10 cm can destroy a satellite, and debris less than 1 cm in size can damage or potentially destroy a satellite.

Orbital debris has degrees of persistence: a few days if the debris is less than 125 miles above the Earth's surface; a few years if the debris is between 125 and 370 miles; decades if the debris is between 370 and 500 miles; centuries if the debris is greater than 500 miles, and essentially forever if the debris is at greater altitudes, especially as one approaches geosynchronous orbit (GEO) altitudes. Thus, at very low altitudes (less than 125 miles) space is quickly self-cleansing; however, peak debris density in low Earth orbit (LEO) occurs at 550 miles, which suggests centuries would pass before the region self-cleans (assuming no additional debris is added during that time). [3]

In the limiting case, orbital space becomes unusable. Don Kessler, former director of NASA's Orbital Debris Program Office, proposed the possibility of a sufficiently dense debris cloud that would lead to a cascade of collisions, ultimately rendering certain orbital spaces unusable [4]. This scenario is popularly known as the "Kessler Syndrome."

2 THEORETICAL ECONOMIC MODELS OF ORBITAL DEBRIS

The first theoretical framework that describes the economic problem posed by orbital debris is developed in [5]. The economic interaction among producers and consumers of satellite services is presented in a two-period model. The model suggests that firms launch too many satellites and choose satellite technologies that create more debris than is socially optimal, i.e., maximizes the overall surplus in the market. This follows directly from the observation that orbital space is a global common, and that satellite operators are self-interested economic actors. To put a fine point on this, orbital slots and spectrum are essentially free inputs, and consequently firms have incentives to over-use these resources, relative to the social optimum.

With respect to debris creation, [5] observe that there are two negative externalities that need to be addressed. First, because firms do not take into consideration the damaging effects of increased debris generated by launch vehicles on other satellites, they launch more than is socially optimal. Second, firms under-invest in debris-mitigating satellite technologies, because they compare the individual marginal benefits and costs of their technology choice, and not costs and benefits that affect all market participants, i.e., social cost and benefits. Reference [5] enumerates a range of policy options, including voluntary guidelines, command and control mechanisms, active debris removal, and debris taxes.

A theoretical economic model that investigates the dynamics of orbital debris is presented in Adilov et al. [6]. This dynamic investment model, with a focus on net expected return, uncovers an orbital debris "economic tipping point" beyond which launches, and the use of orbital space, are substantially impacted as debris densities and resultant damage accelerates. Recall from our earlier discussion that the "Kessler Syndrome" refers to a particular physical model of debris accumulation in orbital space, and the predictions of the model are stark: orbital space is rendered physically unusable at a future point in time. Reference [6] suggests an alternative to the Kessler Syndrome in which orbital space becomes economically unprofitable before it becomes physically unusable; in short, an "economic Kessler Syndrome." This result obtains – for a given debris density and consequent expected damage risk– when the expected marginal revenue from a satellite launch is less than expected marginal cost. In the model, expected marginal revenue equals the sum of discounted expected revenue streams from current and future periods while expected marginal cost equals the sum of the operator's discounted expected marginal costs from current and future periods.

Market forces either accelerate or decelerate the rate of debris creation, and are influenced by factors such as (1) the potential loss of a satellite, (2) the cost of debris avoidance, (3) the shortening of a satellite's useful life or reduced functionality, and (4) shielding costs, among others. Reference [6] also notes that for low relative levels of debris, the relationship between debris and launches is positive and increasing, i.e., firms launch at an increasing rate in response to an increase in orbital debris levels. As debris increases further, expected economic losses from debris increase, and the rate of growth in launches decreases. Finally, debris density reaches a critical "tipping point" where expected profits turn negative, and launches sharply contract.

Reference [6] also implies that firms have, to some degree, countervailing incentives from debris. Clearly, damaged or destroyed satellites reduce expected value. However, as the number of functional satellites decreases, the law of demand suggests that prices of satellite services, and thus profits, increase, ceteris paribus. In short, those satellites that survive yield higher expected returns, and therefore firms with surviving satellites earn above normal profits, and, in some cases, even monopoly profits.

3 CONFIRMATION OF THEORETICAL PREDICTIONS

This study augments the theoretical framework presented in [6] by simulating future economic activity in space and its contribution to orbital debris levels. Because orbital debris is a by-product of activities in space, debris levels increase in response to increased business activity in space. Furthermore, economic forecasts predict that business activity in orbital space will increase at an exponential rate. The quantity of orbital debris will follow a similar path. The simulations confirm that an economic Kessler Syndrome could occur in the absence of orbital debris mitigation, remediation, or other policy actions. However, the economic "tipping point" is highly unlikely to occur in the near to medium term because it requires a level of business activity in orbital space which is at least hundreds of times in magnitude greater than the current level of economic activity, keeping all else constant.

Fig. 1 illustrates a scenario of how an economic Kessler Syndrome could occur in LEO. As predicted in [6], the number of satellites increase at an increasing rate over a long period of time until a peak is reached. Then, the quantity of active satellites will decrease as the orbits become too polluted. Eventually, all active satellites are destroyed by debris and firms will not launch any new satellites. At this point, the economic value of LEO is reduced to zero because the expected marginal revenue from launching a satellite in below the expected marginal cost.

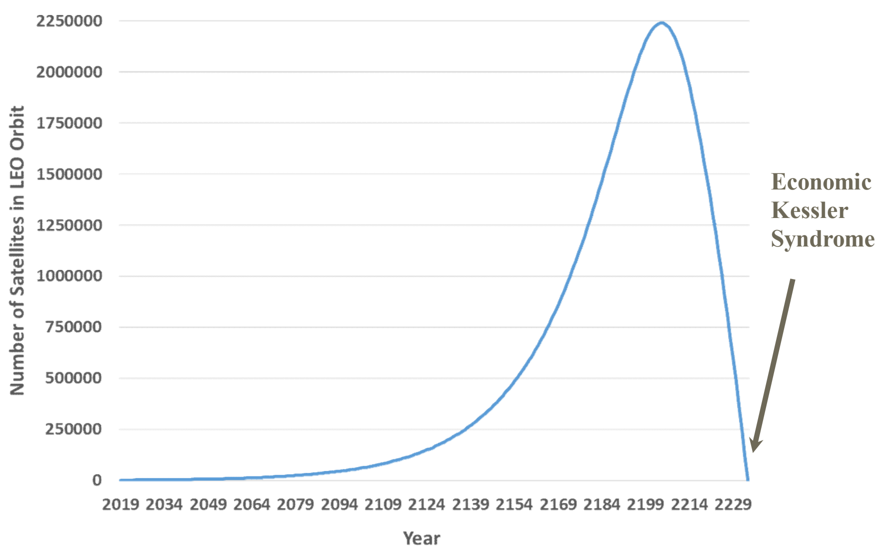

Fig. 1. An example of an economic Kessler Syndrome in a simulated model.

The simulations yield additional insights on the dynamics of orbital debris generation. Fig. 2 describes the expected levels of orbital debris 10 cm or larger in diameter under different policy environments. The baseline simulation assumes 85% compliance rate with the voluntary space debris mitigation guidelines issued by the United Nations Office for Outer Space Affairs [7]. In the baseline simulation, the debris levels increase at an increasing rate and exceed the levels projected by NASA's LEGEND model as we approach the end of the century [8]. The main reason for higher predicted levels of orbital debris is that the economic model predicts a higher number of satellites in LEO (and the emergence of "mega-constellations" of satellites) due to pressure from market forces. This implies that predicting future levels of orbital debris is sensitive to changes in economic factors.

4 ECONOMIC POLICY OPTIONS

As of 2019, a significant fraction of the users of orbital space have been non-commercial (e.g., scientific endeavors, military and state operations). That, however, is changing, in particular with recent approvals in the United States to launch mega-constellations of many thousands of new satellites in low earth orbit. This has at least two implications: (1) more rapid accumulation of debris in certain orbits; and (2) new, large commercial operators may be more responsive to economic incentives than non-commercial operators. This suggests economic theory may become increasing germane to policy makers. In this section we review and briefly explicate policy options found in [5], and provide brief commentary of their potential efficacy relative to orbital debris based on theoretical predictions and simulations of business activity in space. We do not suggest this list is exhaustive, but rather offer these options as a helpful starting point.

Voluntary Guidelines. In 2010, the United Nations Office for Outer Space Affairs issued mitigation guidelines for operators within member states [7]. These guidelines are recommendations, which no member state or operator is obligated to follow. Anti-satellite missile tests conducted by China and by India violate these guidelines. The effects of these events on orbital debris are described in [9] and [10]. As depicted in Fig. 2, if the compliance rate reaches 95%, it will significantly decelerate the rate of orbital debris accumulation. However, it is unlikely that this compliance rate will be reached due to insufficient market incentives. Given that at least some of the guidelines impose direct costs but confer only indirect benefits on operators, the marginal costs of compliance will exceed marginal benefits. In short, it is not individually rational for operators to voluntarily undertake the costs of mitigation. It is important to note that even given heterogeneity among operators in their choice of mitigation technology, voluntary guidelines may not be effective in the long run, because firms will still launch too many satellites relative to the social optimum [5].

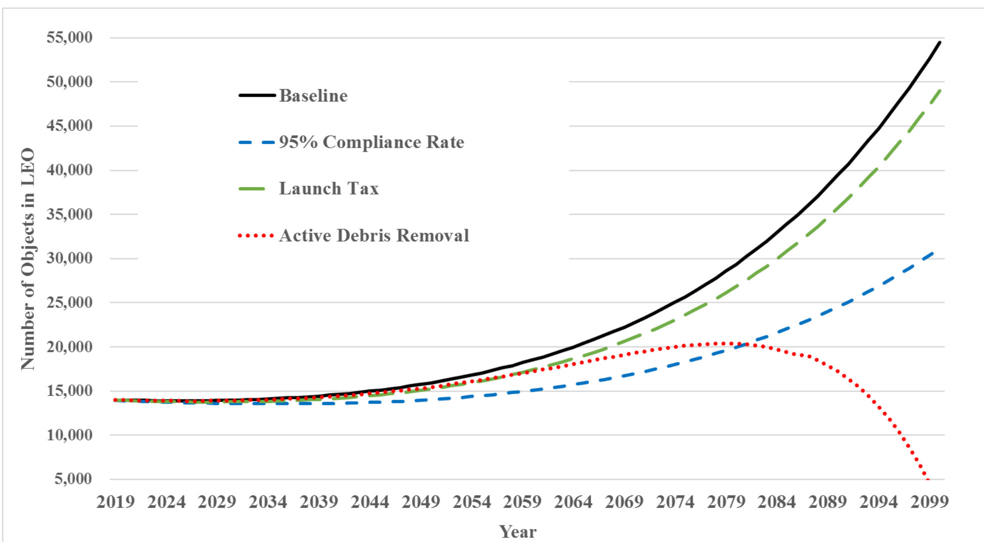

Fig. 2. Number of debris objects 10 cm or larger in diameter under different policy choices.

Command and Control. Command and control measures, such as those regulations issued by the Environmental Protection Agency, often utilize emission limits and technology standards. Thus, in a command and control regulatory environment, firms are required to meet an emissions or technological standard. However, even in relatively simple regulatory settings, command and control measures can lead to economic efficiency losses. Such is the case, for example, with uniform emission standards with cost heterogeneity among firms. In this case, the government must know the marginal abatement costs for each firm, which is likely infeasible. Thus, command and control approaches may fail to meet the requirement of static efficiency. Moreover, if firms are required to use certain abatement technologies, it potentially reduces the incentives to innovate, and induces dynamic inefficiencies. If, however, a command and control approach were feasible, [5] predicts that this would only partially address the problem of excess debris creation, because firms would still launch more satellites than socially optimal. Finally, regulatory arbitrage and the global nature of the satellite industry would likely erode the efficacy of any command and control regime which is unevenly enforced internationally.

Active Debris Removal. The technology for active debris removal is essentially conceptual, and proposed removal systems appear, operationally at least, distant. Moreover, it is not clear how the cost of the debris removal systems will be borne, since no private firm has an economic incentive to develop or implement this technology, and space laws on the ownership of debris might preclude successful implementation. That said, it is not entirely implausible that active debris removal may provide one way forward. For example, Fig. 2 depicts that active debris removal could decrease long-term levels of orbital debris. The simulation assumes that two pieces of orbital debris will be removed in 2020 and that the quantity of debris removed will increase at a rate of 10 percent per year. As noted in [5], "active debris removal appears to have broad support within the scientific community, but will require funding. Thus, a paired measure that is designed to passively reduce debris creation by reducing the number of launches and provide a source of funding for active debris removal might be helpful. To that end, we calculate the optimal Pigovian tax (on launches)."

Debris Taxes and Cap-and-Trade. A debris tax is a price instrument that fixes price and allows the quantity of launches or debris to vary, while cap-and-trade is a quantity instrument that fixes the quantity of launches or debris and allows price to vary. The economic literature relating to both is complex and substantial, and each mechanism has different strengths and weaknesses, often depending on various institutional features. While either mechanism is economically superior to voluntary guidelines from a theoretical perspective, experience shows that successful implementation has been local, regional, or national in scope, and that national self-interest and strategic behavior has precluded successful implementation on a global scale. This is, perhaps, best observed in climate change negotiations. Furthermore, the optimal level of taxes varies with changes in debris levels, the level of technological advancements, and economic conditions. Fig. 2 depicts the effect of a 10-15 percent launch tax. The tax reduces the rate of debris creation. Higher tax rates decrease the rate of debris creation even further, while lower tax rates decrease the rate of debris creation at a lower rate.

5 CONCLUSION

Space debris, an externality generated by expended launch vehicles and damaged satellites, reduces the realized value of space activities by increasing the probability of damaging existing satellites or other space vehicles. Unlike terrestrial pollution, debris created in the production process interacts with firms' final products, and is, moreover, self-propagating: collisions between debris or extant satellites creates additional debris. In a limiting case, collisional cascading could reduce the realized value of certain earth orbits to zero. It is, however, possible, perhaps likely, that increasing debris densities could cause the expected marginal value of orbital activities to fall below expected marginal cost long before a collisional cascade, in short, what Adilov et al. [6] call an "economic Kessler Syndrome." Simulations of economic activity in orbital space confirm the plausibility of this prediction in the long term.

The space-faring community, broadly speaking, understands that orbital debris is a compelling environmental issue that must be addressed to ensure the future use of orbital space. However, policy proposals to remediate orbital pollution may require broad agreement among divergent interest groups, including those across national boundaries, which adds substantial complexity and nuance. As observed in analogous terrestrial settings, successful negotiation and effective regulation can be elusive, even in instances where scientific evidence is compelling. In addition, some policy proposals, such as active debris removal, may require the alignment of policy objectives with economic incentives and the legal environment.

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